

Dynamics of the near response under natural viewing conditions with an open-view sensor

Emmanuel Chirre,^{1,2} Pedro Prieto,^{1,3} and Pablo Artal^{1,4}

¹Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia, Campus de Espinardo (Edificio 34), E-30100, Murcia Spain

²emmanuel.chirre@um.es

³pegrito@um.es

⁴pablo@um.es

Abstract: We have studied the temporal dynamics of the near response (accommodation, convergence and pupil constriction) in healthy subjects when accommodation was performed under natural binocular and monocular viewing conditions. A binocular open-view multi-sensor based on an invisible infrared Hartmann-Shack sensor was used for non-invasive measurements of both eyes simultaneously in real time at 25Hz. Response times for each process under different conditions were measured. The accommodative responses for binocular vision were faster than for monocular conditions. When one eye was blocked, accommodation and convergence were triggered simultaneously and synchronized, despite the fact that no retinal disparity was available. We found that upon the onset of the near target, the unblocked eye rapidly changes its line of sight to fix it on the stimulus while the blocked eye moves in the same direction, producing the equivalent to a saccade, but then converges to the (blocked) target in synchrony with accommodation. This open-view instrument could be further used for additional experiments with other tasks and conditions.

©2015 Optical Society of America

OCIS codes: (330.0330) Vision, color, and visual optics; (330.7310) Vision; (330.4460) Ophthalmic optics and devices; (330.2210) Vision - eye movements; (330.1400) Vision - binocular and stereopsis.

References and links

1. H. Helmholtz, "Ueber die accommodation des auges," *Albr. von Graefes Arch. für Ophthalmol.* **2**(1), 1–74 (1855).
2. G. Westheimer and D. E. Mitchell, "The sensory stimulus for disjunctive eye movements," *Vision Res.* **9**(7), 749–755 (1969).
3. L. Stark, R. V. Kenyon, V. V. Krishnan, and K. J. Ciuffreda, "Disparity vergence: a proposed name for a dominant component of binocular vergence eye movements," *Am. J. Optom. Physiol. Opt.* **57**(9), 606–609 (1980).
4. S. Phillips and L. Stark, "Blur: a sufficient accommodative stimulus," *Doc. Ophthalmol.* **43**(1), 65–89 (1977).
5. E. F. Fincham and J. Walton, "The reciprocal actions of accommodation and convergence," *J. Physiol.* **137**(3), 488–508 (1957).
6. S. J. Judge, "How is binocularity maintained during convergence and divergence?" *Eye (Lond.)* **10**(2), 172–176 (1996).
7. T. N. Cornsweet and H. D. Crane, "Servo-controlled infrared optometer," *J. Opt. Soc. Am.* **60**(4), 548–554 (1970).
8. T. N. Cornsweet and H. D. Crane, "Accurate two-dimensional eye tracker using first and fourth Purkinje images," *J. Opt. Soc. Am.* **63**(8), 921–928 (1973).
9. G. Heron, B. Winn, J. R. Pugh, and A. S. Eadie, "Twin channel infrared optometer for recording binocular accommodation," *Optom. Vis. Sci.* **66**(2), 123–129 (1989).
10. F. Okuyama, T. Tokoro, and M. Fujieda, "Binocular infrared optometer for measuring accommodation in both eyes simultaneously in natural-viewing conditions," *Appl. Opt.* **32**(22), 4147–4154 (1993).
11. R. Suryakumar, J. P. Meyers, E. L. Irving, and W. R. Bobier, "Application of video-based technology for the simultaneous measurement of accommodation and vergence," *Vision Res.* **47**(2), 260–268 (2007).
12. G. Heron, W. N. Charman, and C. Schor, "Dynamics of the accommodation response to abrupt changes in target vergence as a function of age," *Vision Res.* **41**(4), 507–519 (2001).

13. S. R. Bharadwaj and C. M. Schor, "Acceleration characteristics of human ocular accommodation," *Vision Res.* **45**(1), 17–28 (2005).
14. S. R. Bharadwaj and C. M. Schor, "Dynamic control of ocular disaccommodation: first and second-order dynamics," *Vision Res.* **46**(6-7), 1019–1037 (2006).
15. S. S. Chin, K. M. Hampson, and E. Mallen, "Role of ocular aberrations in dynamic accommodation control," *Clin. Exp. Optom.* **92**(3), 227–237 (2009).
16. P. M. Prieto, F. Vargas-Martín, S. Goelz, and P. Artal, "Analysis of the performance of the Hartmann-Shack sensor in the human eye," *J. Opt. Soc. Am. A* **17**(8), 1388–1398 (2000).
17. M. Kobayashi, N. Nakazawa, T. Yamaguchi, T. Otaki, Y. Hirohara, and T. Mihashi, "Binocular open-view Shack-Hartmann wavefront sensor with consecutive measurements of near triad and spherical aberration," *Appl. Opt.* **47**(25), 4619–4626 (2008).
18. K. M. Hampson, S. S. Chin, and E. A. H. Mallen, "Binocular Shack-Hartmann sensor for the human eye," *J. Mod. Opt.* **55**(4–5), 703–716 (2007).
19. E. Chirre, P. M. Prieto, and P. Artal, "Binocular open-view instrument to measure aberrations and pupillary dynamics," *Opt. Lett.* **39**(16), 4773–4775 (2014).
20. E. J. Fernández and P. Artal, "Ocular aberrations up to the infrared range: from 632.8 to 1070 nm," *Opt. Express* **16**(26), 21199–21208 (2008).
21. W. R. Miles, "Ocular dominance demonstrated by unconscious sighting," *J. Exp. Psychol.* **12**(2), 113–126 (1929).
22. T. Yamada and K. Ukai, "Amount of defocus is not used as an error signal in the control system of accommodation dynamics," *Ophthalmic Physiol. Opt.* **17**(1), 55–60 (1997).
23. A. P. A. Beers and G. L. Van Der Heijde, "In vivo determination of the biomechanical properties of the component elements of the accommodation mechanism," *Vision Res.* **34**(21), 2897–2905 (1994).
24. S. Kasthurirangan, A. S. Vilupuru, and A. Glasser, "Amplitude dependent accommodative dynamics in humans," *Vision Res.* **43**(27), 2945–2956 (2003).
25. D. Shirachi, J. Liu, M. Lee, J. Jang, J. Wong, and L. Stark, "Accommodation dynamics I. Range nonlinearity," *Am. J. Optom. Physiol. Opt.* **55**(9), 631–641 (1978).
26. E. J. Fernández and P. Artal, "Study on the effects of monochromatic aberrations in the accommodation response by using adaptive optics," *J. Opt. Soc. Am. A* **22**(9), 1732–1738 (2005).
27. K. M. Hampson, S. S. Chin, and E. A. H. Mallen, "Effect of temporal location of correction of monochromatic aberrations on the dynamic accommodation response," *Biomed. Opt. Express* **1**(3), 879–894 (2010).
28. R. Suryakumar, J. P. Meyers, E. L. Irving, and W. R. Bobier, "Vergence accommodation and monocular closed loop blur accommodation have similar dynamic characteristics," *Vision Res.* **47**(3), 327–337 (2007).
29. Y. Yang, K. Thompson, and S. A. Burns, "Pupil location under mesopic, photopic, and pharmacologically dilated conditions," *Invest. Ophthalmol. Vis. Sci.* **43**(7), 2508–2512 (2002).
30. W. N. Charman, "Near vision, lags of accommodation and myopia," *Ophthalmic Physiol. Opt.* **19**(2), 126–133 (1999).

1. Introduction

The mechanism of accommodation [1] is produced by the contraction of the ciliary muscle which reduces the tension of the zonular fibers on the crystalline lens leading to a change in shape of the lens to focus objects at variable distances. Three main responses are engaged during this process: convergence, accommodation and pupil constriction (miosis). Convergence is the translation of the eyes towards each other in opposite directions [2]. It is caused by retinal disparity [3] and accommodative cues. Accommodation is the change of the dioptric power of the eye. Retinal image blur [4] leads to the automatic adjustment response to maintain a sharp retinal image. Retinal disparity is also an important factor for accommodation [5]. On the other hand, miosis is activated by accommodation (in addition to luminance and other factors) and it is maintained over time as long as the near stimulus is present.

The interaction Accommodative Convergence (AC) and Convergence Accommodation (CA) maintain the visual function stable in time [6] when changes of line of sight are performed under natural binocular viewing conditions.

The study of the near response has been a central problem in Physiological Optics during many decades. However, the dynamic responses of the different factors have been usually investigated separately and few instruments have been developed for the measurement of at least two of the responses [7–11].

The dynamics of accommodation and convergence response is well described under steady state of accommodation. Several approaches [12–15] have been proposed to

characterize accommodation gain, peak velocity, temporal response and latency. However the dynamic interaction of convergence response, accommodation and pupil constriction have not been fully illustrated under natural viewing conditions.

We have used an instrument based on a binocular Hartmann-Shack (HS) [16–18] sensor that allows to measure in real time the three components of the near response simultaneously. The system has been validated and applied in a group of normal subjects to study the accommodative response under a series of controlled experimental conditions where a voluntary accommodation task from far to near was performed.

2. Methods

2.1 Instrument

We used an infrared binocular instrument based on a HS sensor [19]. Figure 1 shows a schematic view of the instrument. The HS sensor consisted of a 150- μm pitch, 5.2-mm focal length lenslet array (MLA 150-5C, Thorlabs GmbH, Germany) and a NIR CCD camera operating at 25 Hz (Hamamatsu C7500-51, Hamamatsu K. K., Japan).

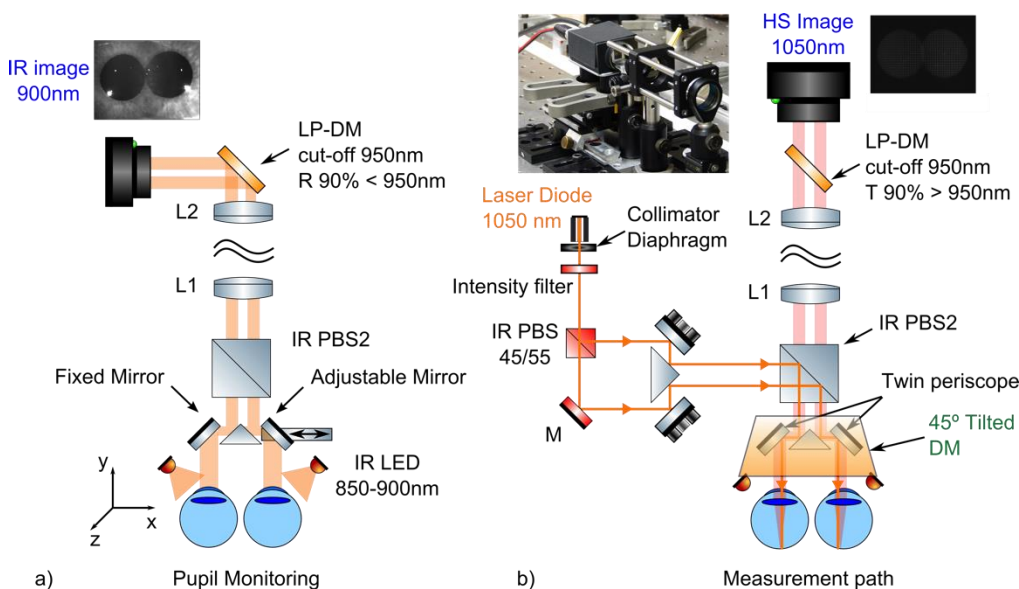


Fig. 1. Schematic view of the binocular HS wavefront sensor. The pupil monitoring path (a) and the measurement path (b) are shown separately. A low pass dichroic mirror (LP-DM) with cut off at 950nm is located before the HS sensor to separate the monitoring (850-900 nm) and the measurements (1050nm) beams.

An invisible infrared source with central wavelength at 1050 nm (Broadband ASE source 1 μm band, Multiwave Photonics, Portugal) is used to perform unobtrusive wavefront measurements of both eyes [20]. A large hot mirror tilted 45°, was used to reflect the illumination beams toward the eyes and the retinal reflections toward the lower level where the HS sensor is located. This provides subject with a large open field of view of the scenes in front. A pupil monitoring camera, in combination with a 900-nm-LEDs, is used to control the correct positioning of pupil's eyes within the sensor. By means of a dichroic mirror (LP-DM) with cut off at 950 nm the measurement and monitoring paths are separated.

The dynamic range of the sensor was evaluated by using of a movable lens illuminated by an IR collimated beam to produce a pseudo-point source at known distances in front of the instrument. Both left and right measurement channels were tested to establish the working range of the binocular open-view wavefront sensor. A large linear ($R^2 = 0.99$) dynamic range of + 4 to -4D diopter was obtained for both channels with an accuracy of 0.025 D.

2.2 Subjects and procedure

Measurements were performed in 8 healthy young subjects (mean age of 27.8 ± 2.4 years). The dominant eye (DE), determined by Miles test [21], was the right eye (OD) for five subjects and the left eye (OS) for other three. The refractive state was of $-0.40 \pm 0.17\text{D}$ at far distance under binocular vision. The mean astigmatism was $-0.22\text{D} \pm 0.38\text{D}$.

To induce the accommodative process, two stimuli generators were placed at 2.75-m and 30-cm in front of the subject's eyes aligned with a point midway between the subject's two pupils, visible in open-view field through the dichroic hot mirror (Fig. 2). The far stimuli generator was a flat LCD monitor and the near one was an OLED micro-display (eMagin, USA). In both cases, the stimuli consisted of a black Snellen E letter (1.3° apparent size) displayed on a white background circle. The light level was adjusted in both devices to be 15 cd/m^2 . Linear polarizers were used to provide high contrast of the target on both displays (not represented in Fig. 2). Both targets were simultaneously displayed through the measurement sequence. The subjects were instructed to perform voluntary far-to-near accommodation a couple of seconds after a sound signal announcing the beginning of the recording sequence.

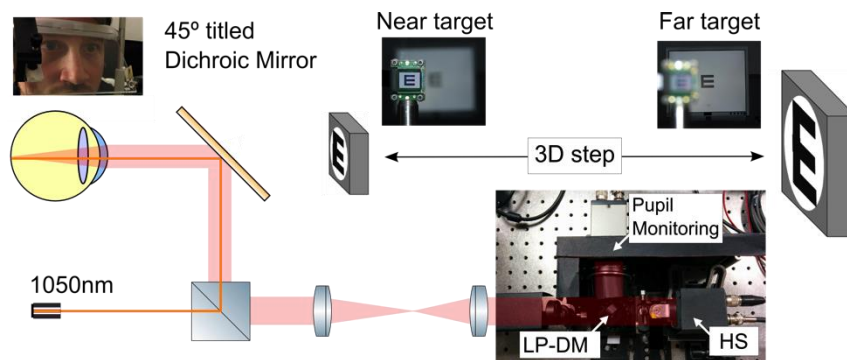


Fig. 2. Lateral view of the instrument illustrating the two levels. The far (2.75 m) and near (OLED micro-display, 30 cm) visual targets are located in the line of sight of the subjects aligned with a point midway between the two pupils. The polarizers and the background circle are not shown.

A set of measurements was performed under binocular and monocular vision with the dominant eye (DE) and non-dominant eye (NDE). Ten-second sequences were recorded three times at 25Hz. For monocular testing; a blocker was placed at 15 centimeters in front of the dichroic mirror to hide the targets from the fellow eye while allowing measurements in both eyes. Subjects were not trained before the experiments given that the field of view was realistic and no complex tasks were required. Accommodation was natural and voluntary.

2.3 Data processing

A custom algorithm based on the background light of the eye is used to detect the both pupils border and center. Pupil diameter is measured by the best circular fit of the pupil boundaries. The grid of micro-lenses centered on each pupil is processed at a selected diameter. Series of wavefront aberrations were estimated for each eye off-line. The binocular pupil tracker includes a blink removal algorithm to allow recording longer measurement sequences. Figure 3 shows a schematic diagram of the full image processing methodology.

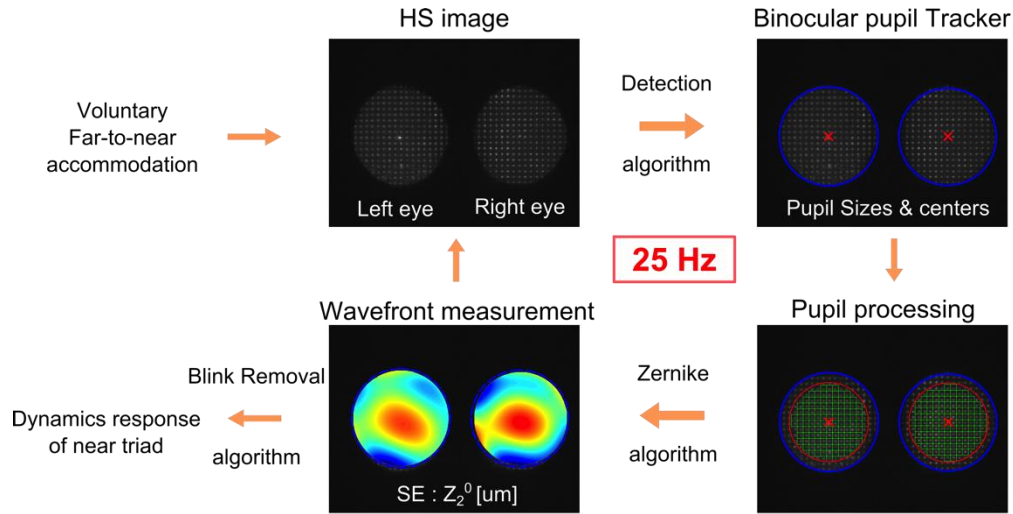


Fig. 3. Image processing schematics.

The accommodation response was quantified by means of the spherical equivalent (SE) obtained from the defocus Zernike coefficient Z_2^0 in micrometers as:

$$SE = \frac{-(4\sqrt{3} \times Z_2^0)}{r^2}, \quad (1)$$

where r is the pupil radius in mm. The HS images were processed for a 4-mm pupil diameter, which included about 120 micro-lenses.

Several approaches can be used to quantify the temporal dynamics of accommodation. Fitting an exponential function [14,22–24], a Boltzmann sigmoid function [26,27], or FFT-based procedures [11,28]. Since we were more interested in comparing the dynamics of accommodation and convergence we used a different approach described later. However, in order to obtain results readily comparable with previous studies, we have also performed an exponential fit using:

$$y = y_0 - a \times (1 - e^{-(t/\tau)}), \quad (2)$$

where y is the accommodation state in diopters as a function of time t , y_0 is the initial value of accommodation, a is the amplitude of the accommodative response, and τ is the time constant, which corresponds to the interval required to produce 63% of the accommodative response. Figure 4 shows examples of exponential fitting of the accommodation responses in three subjects both in binocular and monocular conditions. The use of this functional form allowed only a first order approximation of the accommodation trace and overshoots were generally underestimated. For binocular conditions, the exponential fitting was generally good. On the contrary, monocular accommodation did not always resemble an exponential form in several cases, and fitting was poorer.

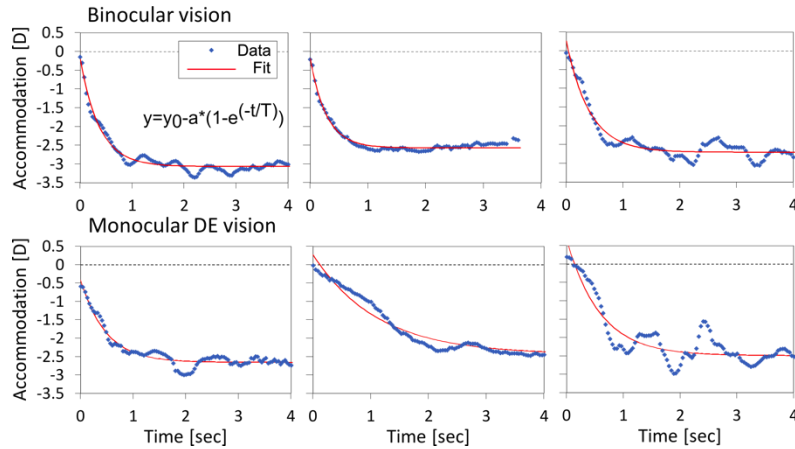


Fig. 4. Examples of exponential fitting of the temporal responses of accommodation in three subjects in binocular (top row) and monocular vision (bottom row). Blue dots: experimental data; red line: fitting. The point corresponding to the onset of accommodation was manually determined.

Instead of using the exponential fitting, which does not correctly model convergence, we have computed the transition time for each process as the interval between two thresholds: average steady state of far accommodation minus standard deviation, and average steady near state plus standard deviation. Both steady state values were calculated by averaging at least 2 second of measurements at the beginning or the end of the 10-s sequence. An example is illustrated in Fig. 5.

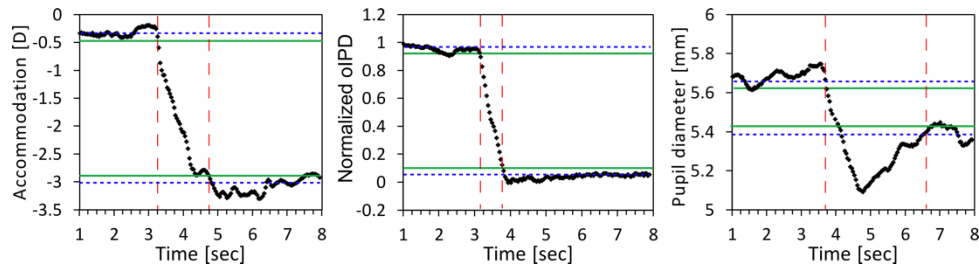


Fig. 5. Example of threshold-based transition time evaluation used to quantify the temporal responses of each process of the near triad: accommodation (left), convergence from the relative interpupillary distance oIPD (center) and pupil constriction (right). Black dots: experimental data; blue dotted lines: steady state level for far and near; green solid lines: threshold values corresponding to average \pm standard deviation; and the total transition time is demarcated by the red dashed lines.

Convergence induces a nasal rotation of both eyes. As a consequence, the interpupillary distance (IPD) decreases. Due to the double periscopic system used to fit both eyes inside a single sensor, the distance between pupils that we obtain is an arbitrarily offsetted version of IPD, which we will denote oIPD. Although it cannot be used in absolute terms, oIPD can be used to study convergence dynamics. Moreover, since the periscopic system remains unaltered throughout the experiment for each subject, the relative change in oIPD, $\Delta oIPD$, is equal to the change in IPD. From this value an estimate of the change in vergence can be obtained by using Eq. (3), which involves the distance from the pupil to the eye's center of rotation, R , and the actual IPD,

$$\Delta V = \frac{\Delta oIPD}{R \times IPD}, \quad (3)$$

where R was assumed to be 11.5 mm from the pupil plane. The actual IPD for each subject was measured with an ophthalmic ruler when looking at the far target (mean value 64 mm).

3. Results and discussion

3.1 Temporal dynamics of the near response

As an example, Fig. 6 shows the dynamics of the near responses for one of the subjects under binocular (left), DE monocular (center) and NDE monocular (right) viewing.

All three processes have a faster response under binocular viewing conditions (blue data) compared to the monocular case. Convergence (interpupillary distance) is the fastest process, taking on average 0.80 ± 0.17 sec. Accommodation takes 1.22 ± 0.28 s on average (threshold method) but it is interesting to note that if the threshold is set to 90% of its initial value, the duration would be reduced to 0.58 ± 0.25 sec. An accommodative overshoot combined with a decrease of the accommodation slope at the end of accommodation explain mainly this time difference when the threshold is changed.

Under monocular DE and NDE, both convergence and accommodation exhibit a similar temporal response. Accommodation takes 2.20 ± 0.67 s and 2.22 ± 0.58 s on average for DE and NDE respectively, while convergence takes 2.27 ± 0.80 s and 2.10 ± 0.69 sec. The slopes of both responses are lower compared to the binocular case, which implies a velocity reduction from the beginning of the accommodation process. The pupil constriction shows also the slowest temporal response with significant differences among subjects. The fluctuations of the pupil size are greater and the miosis amplitude is lower.

When using the exponential function, the temporal response of accommodation was 0.28 ± 0.10 sec, 0.55 ± 0.32 s and 0.52 ± 0.33 s under binocular, monocular DE, and monocular NDE vision respectively. These values are significantly lower than those estimated with the threshold method and comparable to those obtained in the literature with a similar type of analysis [24,25]. The convergence and pupil miosis were not analyzed with this method since they do not follow an exponential curve.

An accommodation task of 3 diopters is on average two times slower under monocular fixation than under binocular and no significant differences have been found between DE and NDE monocular viewing. The binocular interaction convergence-accommodation increases the speed of the accommodation response while monocularly the accommodation induces convergence even in absence of retinal disparity.

Figure 7 shows the average changes of accommodation, convergence and pupil size (vertical axis) against the transition time (horizontal axis) for each process. The amount of accommodation was obtained by means of Eq. (2), and convergence was estimated with Eq. (3). The difference between accommodation and convergence estimates was within $\pm 0.1D$ under binocular vision and $\pm 0.2D$ for monocular conditions. The slightly larger difference for monocular vision could be due to errors in convergence caused by the absence of retinal disparity or by the slight shift in the pupil center as the pupil size changes, which is more noticeable for larger pupils, as is the case in monocular conditions [29].

The accommodation response was about 2.32 D under binocular viewing, which corresponds to a lag of accommodation of 0.65 D on average. Monocularly, the mean lag of accommodation was 0.86 D on average. These values are slightly larger than those typically found in the literature of about 0.5D for a 3D demand [24,30]. Our results combined a lag for high dioptric stimulus demands and a lead for low levels that reduced the total step of accommodation. The use of low luminance targets could be related to this behavior, as well as the use of a large letter (1.3° apparent size.) as stimulus, which reduced the need to perform an accurate accommodation.

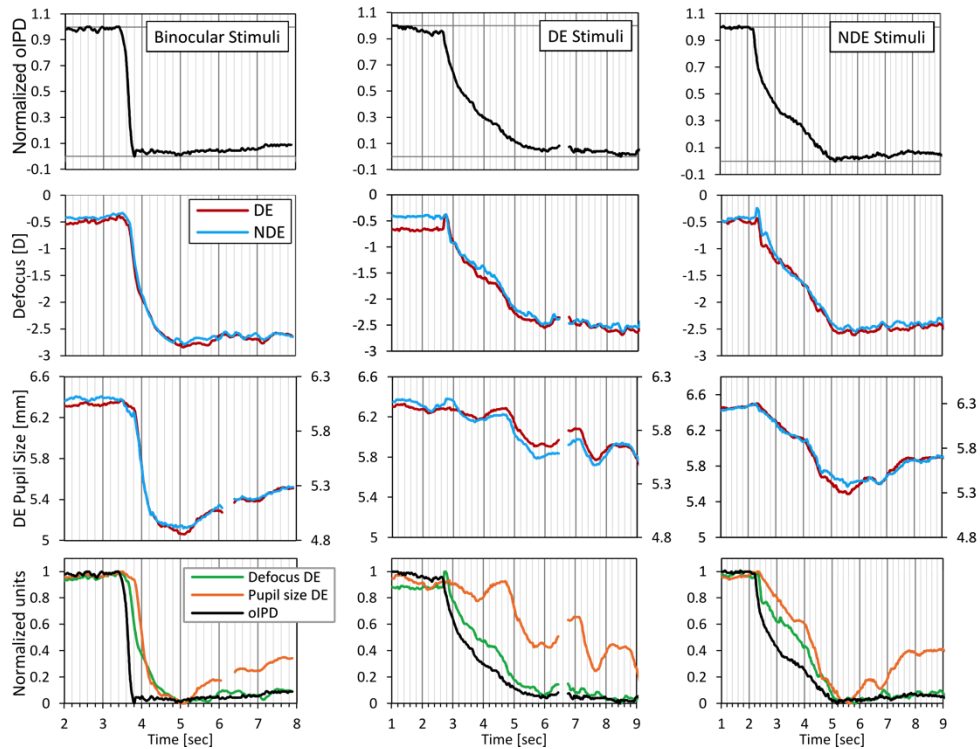


Fig. 6. Responses of interpupillary distance, accommodation and pupil diameter as a function of time under binocular (left), monocular DE (center) and NDE (right) for one subject. Top row: normalized relative inter-pupillary distance. Center row up: Spherical equivalent. Center row down: Pupil Diameter. Bottom row: Normalized comparison of the three responses.

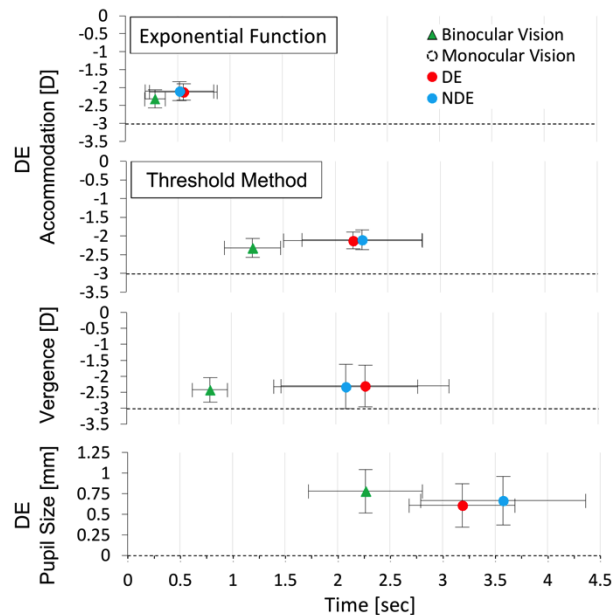


Fig. 7. Average changes in accommodation (by means of an exponential fitting and a threshold method), convergence (center) and pupil constriction (bottom). Green, red and blue symbols represent binocular and monocular DE and NDE viewing conditions respectively. Accommodation and pupil size changes were measured in both eyes for each condition.

3.2 Pupil displacements/convergence

Figure 8 shows the measured defocus of both eyes together with the displacements of the pupil centers (three repetitions for the same subject) under binocular (left), monocular DE (center) and monocular NDE (right) viewing conditions. DE and NDE measurements results are shown in red and blue respectively. The origin for pupillary position was arbitrarily taken as the initial position of the DE. The apparent interpupillary distance, oIPD, is represented in black.

Under binocular viewing (left panels), the two eyes present a strong similarity in their motion in the nasal direction and appear to be synchronized which is consistent with the expected behavior. Both eyes follow an analogous trajectory in opposite directions towards each other converging to the near stimulus (Fig. 9(a)). A fast and accurate convergence is performed when binocular retinal disparity and blur accommodation cues are available to drive accommodation. Both CA and AC processes are stimulated which makes the whole accommodative reflex stable and efficient.

Monocularly with the dominant eye DE (central panels), binocular retinal disparity is missing, and only monocular blur in the stimulated eye is available to drive accommodation. In these conditions, convergence is driven by accommodation (AC).

When the accommodation process starts, the stimulated eye moves fast in the nasal direction in order to fixate on the near target, while the fellow eye shifts in the temporal direction opposite to the expected direction in a moment resembling a saccade. Both pupil motions are still triggered simultaneously. This movement occurs during a short time maintaining the apparent interpupillary distance. Then as the accommodation progresses, the fellow eye displacement is switched to nasal direction synchronized with accommodation, which as previously mentioned, is slower than for binocular vision. This is a peculiar behavior in both eyes that has been observed for all the subjects participating in the study.

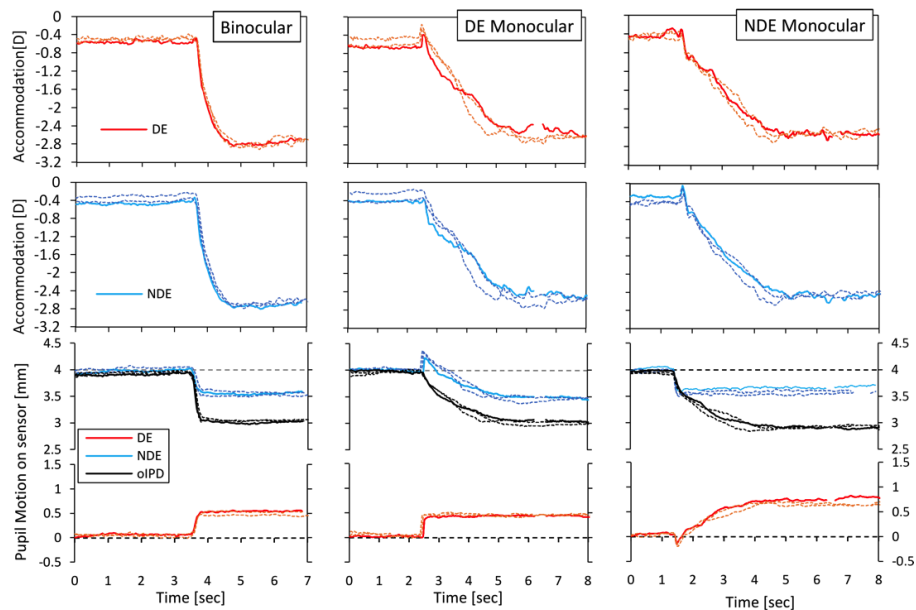


Fig. 8. Examples in one subject of DE (top row) and NDE (center row) accommodation results and pupil displacement (bottom row) when far-to-near accommodation is performed under binocular (left column), DE (center column) and NDE (right column) monocular fixation. Red and blue lines correspond to DE and NDE measurement respectively. In the bottom row, oIPD is represented in black. Two more repetitions in the same subjects are displayed with dotted lighter lines in order to give an idea of repeatability.

The shift of the fellow eye in the temporal direction under monocular conditions could probably be explained by an erroneous interpretation of the scene. Since disparity is absent when the subject switches between stimuli, the distance information is not available and the near target position is interpreted as a lateral displacement of the far target triggering a saccadic movement of both eyes (Fig. 9(b). step 1). However, monocular blur induces accommodation, which in turn induces accommodative convergence (Fig. 9(b). step 2).

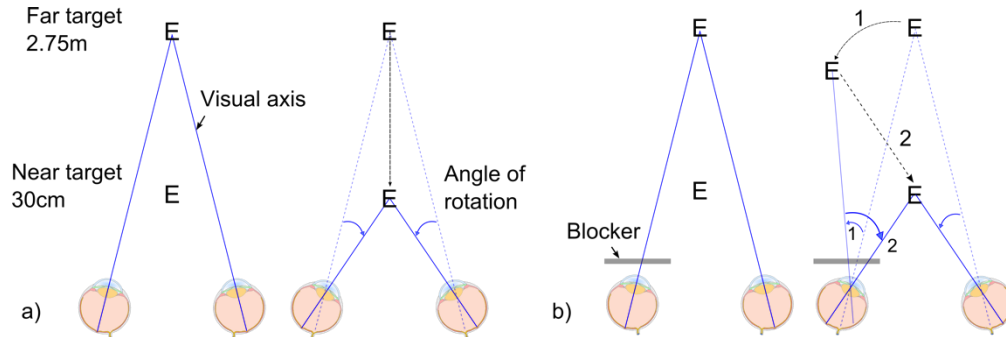


Fig. 9. Schematic representation of the movement of the two eyes when far-to-near accommodation is performed under binocular a) and monocular vision b). Binocular convergence involves simultaneous nasal rotation of both eyes. Conversely, monocular convergence is a two-step process: fast synchronized rotation of both eyes in a saccadic-like movement (1) followed by a slow nasal rotation of the blocked eye synchronized with accommodation (2).

Another distinctive feature of monocular accommodation in some subjects was a brief disaccommodation of the stimulated eye. The blocked eye did not show this feature nor was it present under binocular vision and it was not concordant with pupil motion. The peak magnitude was lower than 0.2 D on average across repetitions for every subject showing this feature. We do not have a plausible interpretation of this behavior under monocular viewing. Subjects were aware on the task to be performed (far-to-near accommodation) and the position of the near target was known and visible during the measurements. In addition, this phenomenon was not present in some subjects and only in one eye for others (Fig. 10).

Figure 10 shows the normalized behavior of accommodation in both eyes and convergence (oIPD) for the 5 subjects with DE = OD. Under binocular vision, 4 of them had convergence significantly faster than accommodation (left panels). The dotted lines show the beginning of the convergence process. A delay is measured of 0.12 ± 0.08 ms between convergence accommodation onset was measured with the threshold method. However, it should be pointed out that the initial dynamics of these two processes are sometimes different, affecting the accuracy of our delay estimates. Under monocular conditions, no delay was observed. Defocus and convergence were engaged synchronously and they were accomplished together.

These experiments were performed with natural accommodation in each subject. It has been found [25,26], that higher order aberrations may affect the accommodation responses. Although the impact of this factor is probably smaller than binocularity, further experiments with a future modification of our experimental system able to manipulate the subjects' aberrations would be required to completely clarify the relative impact of each factor.

Another aspect that could be investigated in the future is the effect of age. In particular, the responses measured on early presbyopic subjects could help to better understand the deterioration of the accommodation mechanism.

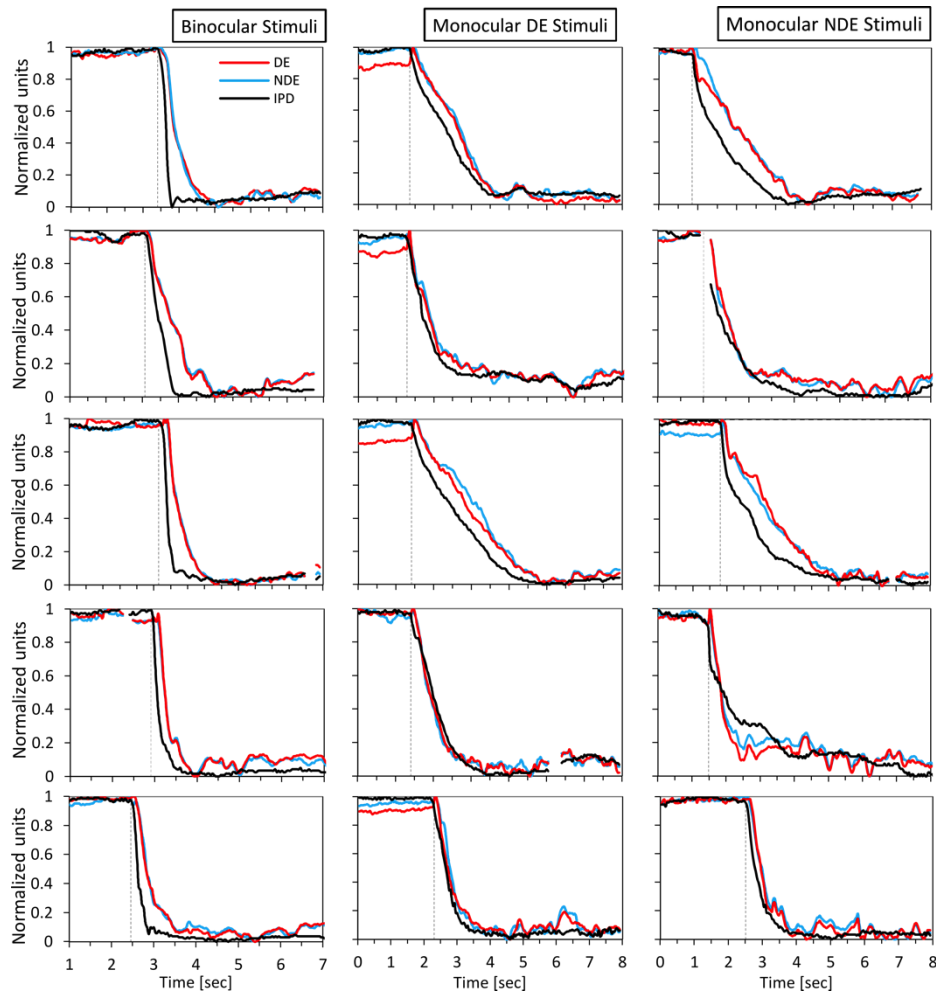


Fig. 10. Behavior of convergence and accommodation of five subjects with right dominant eye, under binocular (left) and monocular DE (center) and NDE (right) vision. Normalized DE and NDE accommodation is shown in red and blue respective and normalized oIPD in black.

4. Conclusions

We have used a custom developed infrared Hartmann-Shack binocular wavefront instrument to study the near response under realistic viewing conditions. The dynamic responses of 8 normal subjects were measured when far-to-near accommodation was performed voluntarily under binocular and monocular DE and NDE conditions.

The three reflexes (accommodation, convergence and pupil size) showed faster temporal response for binocular vision than under monocular conditions. The rotation of eyes was triggered simultaneously and synchronized. The dynamics of convergence response was performed fast and efficiently when binocular retinal disparity and blur accommodation were available with accommodation response trailing.

Under monocular vision, accommodation and convergence response was slower and presented higher inter-subject variability. A shift in temporal direction of the fellow eye was interpreted as an initial saccadic movement when accommodation started. Then the fellow eye movement was synchronized with changes of accommodation. Monocular blur induced accommodation, which in turn induced accommodative convergence.

The mean time constant of the exponential fitting to the accommodation was 0.283 ± 0.098 s for binocular vision, 0.555 ± 0.322 s for DE monocular vision, and 0.517 ± 0.327 s for NDE monocular vision. When using the threshold method, accommodation required about 1.22 ± 0.28 s to be accomplished binocularly, 2.20 ± 0.67 s and 2.27 ± 0.80 s under monocular vision.

These results further suggest the important role of binocularity on the accurate dynamic response to near targets. This type of open view instrument can be of interest for additional experiments where other specific visual tasks (for instance when using 3D displays) are used.

Acknowledgments

This research has been supported by the European Research Council Advanced Grant ERC-2013-AdG-339228 (SEECAT) and the Spanish SEIDI, grant FIS2013-41237-R. E. Chirre acknowledges a FPI predoctoral fellowship by the 'Ministerio de Ciencia e Innovacion', Spain (FIS-2010-14926).